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14. ABSTRACT

The words "Left Handed Materials" in the Title were one early way of expressing what is now termed "Negative Index (of refraction) Metamaterials" or NIMs In our proposal for this grant we focused on four general Goals:
1. Lowering the losses for the wire and SRR (split ring resonators) based unit cell construction designed to produce a desired negative permittivity (ε) and negative permeability (μ) set of values.
2. Extend the theoretical concepts for making new types of NIMs, and then designing the new unit cells by the appropriate numerical simulations of Maxwell's Equations.
3. Extend the range of NIM frequencies from THz to the Infrared and potentially the optical.
4. Find Applications of interest to the Air Force using improved negative permittivity and negative permeability unit cells.
We summarize the examples of the progress made and discussed in the previous three Progress Reports in the Technical Final Performance Report attached herein.

15. SUBJECT TERMS
Left Handed Material, NIM (Negative Index (of Refraction) Metamaterial, SRR (Split Ring Resonators)

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Reporting Period: March 01, 2004 to December 31, 2007 (with NCE)
Title: **Left Handed Materials Research for Air Force Applications**
Program Manager: Dr. Harold Weinstock

I. Executive Summary

At the beginning of this grant the words "Left Handed Materials" in the Title were one early way of expressing what is now termed "Negative Index (of refraction) Metamaterials" or NIMs. Our research group developed and demonstrated the first proof of the existence of Negative Index of Refraction by designing, numerically simulating, and fabricating metamaterial based samples and then performing confirming experiments at microwave frequencies. In our proposal for this grant we focused on four general Goals:

1. Lowering the losses for the wire and SRR (split ring resonators) based unit cell construction designed to produce a desired negative permittivity (ε) and negative permeability (μ) set of values.

2. Extend the theoretical concepts for making new types of NIMs, and then designing the new unit cells by the appropriate numerical simulations of Maxwell's Equations.

3. Extend the range of NIM frequencies from THz to the Infrared and potentially the optical.

4. Find Applications of interest to the Air Force using improved negative permittivity and negative permeability unit cells.

We summarize the examples of the progress made and discussed in the previous three Progress Reports in Section II below.

Personnel Involved: Professor Sheldon Schultz (Principal Investigator)
Dr. David C. Vier (Senior Project Scientist)
Mr. Aleksander Simic (Graduate Student)

II. Technical Report

First Report: (Goal 1) Experiments on single gap SRRs made of superconducting Low Tc (Nb) foil or wires showed the expected higher Q resonances at cryogenic temperatures, and the unexpected fact of a significant Q remaining even in applied uniform DC magnetic fields of 5 KG. We then exploited that high Q retention to perform field modulation studies using the effects of electron spin resonance for a paramagnetic material (DPPH marker) deposited on the centers of the individual SRRs.

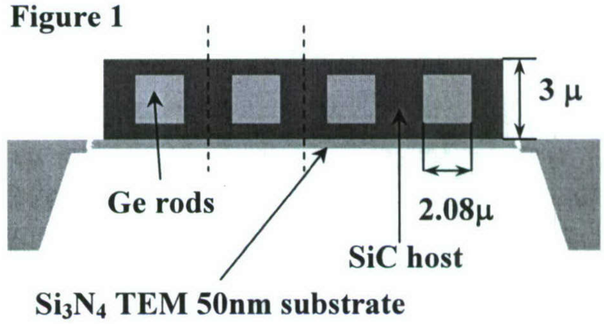
We extended our designs for a NIM with a set of desirable parameters (n= -1, Z= +1) based on a High Tc superconducting wire and SRR unit cell with a typical high ε'=24 LSAT substrate. We were introduced to Dr. John Talvacchio (of the Northrup Grumman company) who agreed to collaborate and supply YBCO wafer based SRR components for testing.

We established a collaboration effort with a company that specialized in the manufacture and use of VTD (voltage tunable dielectrics) for microwave device applications. Based on this interaction we designed NIM unit cell structures that would be practical to incorporate at zero applied control voltages, and which would be appreciably modified at practical control voltages.

Second Report: (Goal 2) In parallel with the NIM work at microwave frequencies, we have devised ways to extend the NIM concepts to entirely new unit cell designs based on traditional continuous materials, and (Goal 3) to use these designs to achieve NIM behavior at frequencies from THz to the mid IR.

The new design concept is to create a 2D negative index unit cell structure that combines a positive large permittivity (ε') set of long rods to generate a negative permeability (μ') along the rod axis, which is surrounded by a host material which has a negative (ε') and a positive permeability (μ'), and which in combination ends up having an effective index of n= -1 (for example) with an effective surface impedance Z= +1, at the desired operating frequency. The actual structure proposed for the MURI competition is shown in a Top View in **Figure 1**. The mechanism for achieving the –ε', +μ' host is to utilize the high frequency side of the Polariton resonance that occurs when the light line intersects the transverse optical (TO) phonon. The mechanism for achieving a +ε', -μ' for the "rods" is to use the low frequency side of the lowest Mie resonance when excited by an Electric field transverse to the rod axis.

Figure 1



It turns out that at a wavelength of 10.6 microns Ge rods and a SiC host for the proper choice of dimensions can have the desired working conditions of effective n= -1, Z=+1 as desired. This work enabled us to submit a "White Paper" for an AFOSR MURI competition for which we received approval to submit a full proposal.

Third Report: (Goals 2 and 3) As discussed above, we were invited to submit a full MURI proposal which required the selection and collaboration of a suitable Group of highly skilled experimental and theoretical physicists to devote an appreciable effort to analyze and generate the special sample selection, preparation, methods of simulation, techniques of fabrication and specific means of verification of a true negative index behavior at effective n= -1 and Z=+1. One special feature was a solution of the critical question, how to make measurements on flat planar samples that would yield unique values of the index and its negative sign. The answer we produced required special implementation of interference spectroscopy as a function of several laser lines between 28 to 29 THz. We were able to get the cooperation of a company which had the ability and interest to join our academic research group and commit to building the interferometer. Unfortunately, we were not selected for funding.

With direct relationship to Goal 4 we embarked on a novel approach towards using negative permeability design concepts for development of high efficiency sub-wavelength antennas (initially) in the cellular frequency range. These antennas are of simple construction, and can be directly matched to the typical 50 ohm source without the need for Baluns or matching networks. We believe these antennas can be used for UAV and other applications of direct interest to the Air Force over a broader range of frequencies, and their further development was the main thrust in the submitted Renewal Proposal.